CHAPTER 4

SPILLWAY CHUTE

Section I. Basic Considerations

4-l. General.

a. The chute is that portion of the spillway which connects the crest curve to the terminal structure. The term chute when used in conjunction with a spillway implies that the velocity is supercritical; thus the Froude number is greater than one. When the spillway is an integral part of a concrete gravity monolith, the chute is usually very steep. Chutes as steep as 1.0 vertical on 0.7 horizontal are not uncommon. The steepness thus minimizes the chute length. Chutes used in conjunction with embankment dams often must be long with a slope slightly steeper than the critical slope. This long, prominent structure is termed a chute spillway. The designs for long spillway chutes and steep chutes on concrete dam monoliths involve many of the same geometric and hydraulic considerations. Due to the extreme slope and short length of a steep chute, many of the hydraulic characteristics that become prominent in spillway chutes have insufficient time to develop prior to reaching the terminal structure.

b. Hydraulic characteristics that must be considered in the design of a chute are the velocity and depth of flow, air entrainment of the flow, pier and abutment waves, floor and wall pressures, cavitation indices, superelevation of the flow surface at curves, and standing waves due to the geometry of the chute. Obtaining acceptable hydraulic characteristics is dependent upon developing proper geometric conditions that include chute floor slope changes, horizontal alignment changes (curves), and sidewall convergence. This chapter presents data to assist the designer in obtaining an acceptable chute design. A model study is recommended to confirm any design that involves complex geometric considerations and/or large discharges and velocities.

4-2. Sidewalls. The height of a chute sidewall should be designed to contain the flow of the spillway design flood. The flow profile of the spillway design flood can be computed using the methods discussed in Chapters 2 and 3. The computed profile may require adjustment to account for the effects of pier end waves, slug flow or roll waves, and air entrainment. Sidewall freeboard is added above the adjusted profile; as a mimimum, two feet of freeboard is recommended. A conservative, empirical freeboard criterion recommended by USBR (item 77) is as follows:

$$\text{Freeboard} = 2.0 + 0.025Vd^{1/3} \tag{4-1}$$

where V and d are the mean velocity and mean depth in feet, respectively, in the chute reach under consideration.

a. Pier End Waves. Supercritical flow expands after flowing past the downstream end of a spillway pier. The expanding flow from each side of a pier will intersect and form a disturbance which is termed a pier end wave. These waves travel laterally as they move downstream. Multiple piers will cause the formation of a diamond pattern of waves within the chute. The impact at the intersection of the flow can be so severe that a rooster tail-like plume of water will form. A large plume was noted during the Libby Dam model studies (item 58) and was of sufficient concern to require the design of a streamlined pier end to eliminate it. Referring to Figure 4-1, the location on the sidewall where the wave from the first pier intersects the wall can be estimated by the equation:

$$z = \frac{x}{\tan\left[\sin^{-1}\frac{(gy)^{1/2}}{V_s}\right]} \qquad (4\text{-}2)$$

where

- z = distance from downstream end of pier to wave and wall intersection, feet
- x = distance from first pier to the wall
- y = depth of flow
- V_s = surface velocity of flow, ft/sec

Equation 4-2 is qualified by the following conditions: The wave height at the end of the pier should be relatively small compared to the depth of flow and the velocity should be taken as the surface velocity which can be approximated by twice the average velocity. Flow disturbances from pier ends should be contained within the chute. The magnitude of the pier end wave height is difficult to determine without a model study. For a design without the benefit of a model study, an additional 25 percent of the depth of flow should be included in the sidewall height to account for pier end waves.

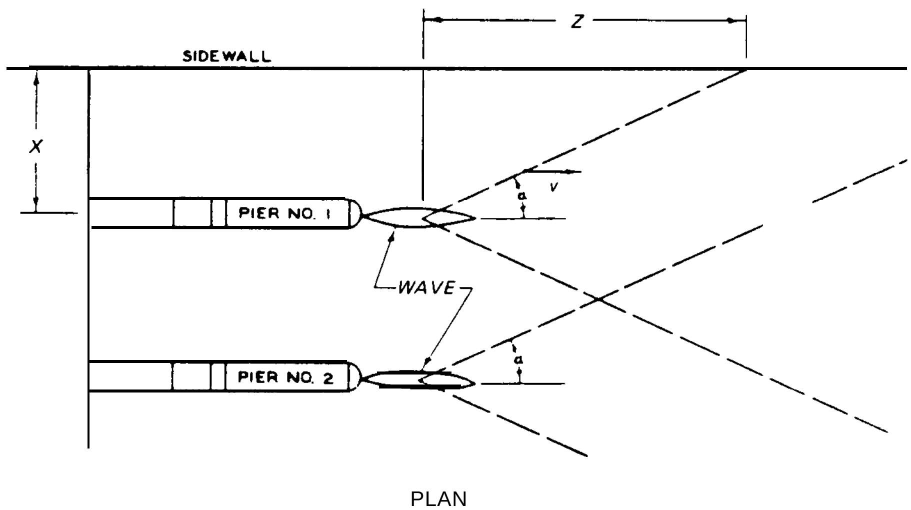

Figure 4-1. Pier end waves downstream of spillway piers

b. Slug Flow. Slug flow or roll waves may form in long chutes and should be considered in sidewall height determinations. Observations of existing chutes indicate that these waves can reach a maximum height of approximately five percent above the mean depth. Knowledge of this type of instability is limited; therefore, further study of the phenomenon in the prototype is suggested when the condition is known to exist.

c. Air Entrainment. When air is entrained in supercritical flow, there is an increase in volume, sometimes called bulking, which will result in a greater depth of flow. This effect is noticeable in flow with Froude numbers greater than 1.5. Air entrainment must be considered in the design of chute sidewalls, bridges, or other features dependent upon the water surface profile. EM 1110-2-1601, provides the designer with a basis for increasing the flow depth due to bulking. Plate 4-1, reprinted from EM 1110-2-1601, defines the ratio of flow depth with and without air to the Froude number.

4-3. Convergent and Divergent Chutes.

a. Convergent Chute. Laboratory and field evaluation by Cox (item 11) has resulted in design criteria and guidance applicable to spillway chutes having convergence affected by horizontal curves of long radii. Optimum chute flow conditions prevail when the following criteria are satisfied, and a design that meets these criteria should perform adequately. The design flow Froude number should gradually increase continuously throughout the convergence. Optimum flow conditions occur with a crest formed by the break in invert grade or by a low sill formed as an integral part of the chute slope. However, for structural or economic reasons, the use of a spillway crest with a toe curve may be required, and less favorable flow conditions in the chute will result. Curving the chute crest in the form of a horizontal arc is noted not to appreciably affect flow conditions in the converging chute. Straight-lined converging walls in the vicinity of the crest are desirable to effect the initial convergence of the flow. Parallel walls in this vicinity should be avoided. The straight-lined walls should extend upstream beyond the crest into the subcritical flow area. These straight-lined walls should not extend downstream beyond the point where the Froude number exceeds 1.5. Straight-lined walls should have a convergence factor of $\Delta L/\Delta W \geq 5.0$, where ΔL is the change in center-line length and ΔW is the change in width for center-line length increment ΔL . Chute walls curved horizontally with long radii should be used when the local Froude number exceeds 1.5. These curved walls should be designed so that the convergence factor down the chute complies with the relationship:

$$\frac{\Sigma\Delta L}{\Sigma\Delta W} \geq \frac{1}{0.382 - 0.116F} \qquad (4\text{-}3)$$

where

$\Sigma\Delta L$ = center-line station distance from the intersection of the crest axis and sidewall

$\Sigma\Delta W$ = accumulated sidewall convergence beginning at the intersection of the sidewall with the spillway crest

F = local design flow Froude number at the station $\Sigma\Delta L$ for the design flow

The minimum recommended design value of $\Sigma\Delta L/\Sigma\Delta W$ is 5.0. When the Froude number exceeds approximately 3.25, parallel walls are considered necessary. Vertical chute walls in the converging section are preferable to sloping walls due to the adverse effects sloping walls have on the local Froude number. When sloping walls are used, these walls should be sloped normal to the chute invert slope rather than normal to the horizontal. Hydraulic model studies are usually conducted to verify the design of a convergent chute spillway.

b. Divergent Chute. When site or economic conditions indicate that a short crest length and a widened terminal structure are desirable, diverging chute walls will be required. Model studies conducted by USBR (item 77) provide examples of designs required for chute type of spillways. USBR uses a straight crest and recommends a maximum sidewall flare angle, α , of

$$\tan \alpha = \frac{1}{3F_1} \qquad (4\text{-}4)$$

where F_1 is the average Froude number of the flow at the location in the reach where the flare originates.

Section II. Chute Spillways

4-4. General. Chute spillways are normally designed to minimize excavation. This is accomplished by setting the invert profile to approximate the profile of the natural ground. Profile changes in both the vertical and horizontal alignment may be involved when obtaining a minimum excavation design. The chute spillway is essentially a high-velocity channel, the design of which is discussed in detail in EM 1110-2-1601. The primary concerns for the design of the chute spillway are to provide an invert slope that will ensure supercritical flow throughout the chute for all discharges, and to provide a design of piers, abutments, and sidewall transitions and bends that will minimize wave disturbances.

4-5. Invert and Water Surface Profile. Flow characteristics near critical depth are unstable, and excessive wave action or undulations of the water surface can occur. To avoid these instabilities, supercritical flow depth less than 0.9 of the critical depth or a Froude number greater than 1.13 is necessary. Computations of depth, velocity, and Froude number should consider the boundary layer development over the crest and downstream to the critical point where fully turbulent flow is developed. The remainder of the chute should be analyzed by an open channel flow method for determining energy loss for fully turbulent flow, A relatively large roughness value should be used for the determination of flow stability and water surface profiles. To assess flow stability for all operating conditions, velocity and depth computations for the full range of discharge are suggested. A second analysis of velocity and depth throughout the chute should be undertaken with a relatively small roughness value. The data derived from the second set of analyses are for consideration in the design of the sidewall alignment, sidewall height, and terminal structure design.

4-6. Invert Pressure. Details of the chute floor slabs deserve careful attention in the interest of structural safety and economy. Structural aspects are discussed in EM 1110-2-2400. In addition to the static uplift pressures from reservoir or tailwater seepage, there are two conditions of hydrodynamic uplift that must be considered. The first consideration is at vertical curves from a steep slope to a flatter slope. Transmission of high boundary pressure through construction joints is possible and should be analyzed in determining uplift on chute slabs. Construction joints should be excluded from locations that include vertical curves from a steep to flatter slope. Theoretical studies and model and prototype data indicate that the pressures resulting from the change in direction of the flow are changing continuously throughout the curve and are influenced by the curve radius, flow velocity, and discharge. Pressures immediately upstream and downstream of the curve are influenced by the invert curvature but reduce rapidly to hydrostatic pressures a short distance away from the curve. These pressures can best be evaluated by means of a flow net or model study. An estimate of the pressures can be obtained by extrapolating the pressure pattern of the curve. Flip bucket pressures discussed in paragraph 7-21 are applicable in this analysis. The second consideration is at vertical curves from a flatter slope to a steeper slope. Negative pressures can occur unless the vertical curve is properly designed. The design of this type of vertical curve is similar to a parabolic drop from a tunnel exit portal to a stilling basin floor. The floor profile should be based on the theoretical equation for a free trajectory:

$$y = -x \tan \phi - \frac{gx^2}{2(1.25V)^2 \cos^2 \phi} \qquad (4\text{-}5)$$

where

x and y = horizontal and vertical coordinates measured from the beginning of the curve, feet

ϕ = angle between the horizontal and the floor at the beginning of the trajectory, degrees

To prevent flow separation from the floor, the average velocity used should be derived from flow computations using a relatively small roughness value. As a conservative measure this velocity as used in equation 4-5 has been increased by 25 percent. If site conditions require a design whose trajectory is steeper than that described by equation 4-5, model studies are recommended; and special construction practices must be specified to obtain surface tolerances and other provisions such as boundary aeration, so that the chute floor surface is compatible with low boundary pressure design.